

Tests of CPT Symmetry in B^0 - \bar{B}^0 Mixing and in $B^0 \rightarrow c\bar{c}K^0$ Decays

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Using the time dependences for the decays $\Upsilon(4S) \rightarrow B^0\bar{B}^0 \rightarrow (\ell^\pm X)(c\bar{c}K_{S,L}^0)$, we determine the three CPT-sensitive parameters $\text{Re}(\mathbf{z})$ and $\text{Im}(\mathbf{z})$ in B^0 - \bar{B}^0 mixing and $|\bar{A}/A|$ in $B^0 \rightarrow c\bar{c}K^0$ decays. We find $\text{Im}(\mathbf{z}) = 0.010 \pm 0.030 \pm 0.013$, $\text{Re}(\mathbf{z}) = -0.065 \pm 0.028 \pm 0.014$, and $|\bar{A}/A| = 0.999 \pm 0.023 \pm 0.017$, in agreement with CPT symmetry. The $\text{Re}(\mathbf{z})$ result provides a limit on one component of Lorentz-symmetry violation.

Trying to solve the puzzle of two different K^+ mesons with opposite parity, Lee and Yang¹ found in 1956 that there were no convincing tests of P conservation in weak-interaction processes. Soon, two experimental groups concurrently proved that P is not only violated in K^+ decays, but also² in the decay chain $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ and³ in β decays of ^{60}Co . CP violation was discovered⁴ in 1964 in the decays $K^0 \rightarrow \pi^+\pi^-$ at late decay times. In the following years, many authors asked if CPT could also be violated in Nature despite its validity in Lorentz-invariant QFT. CP violation implies that T or CPT or both are also violated. Bell and Steinberger⁵ proposed in 1965 separate tests of T and CPT using a unitarity relation with the sum of CP violations in all K^0 decay modes. With then all essential inputs measured, Bell-Steinberger unitarity resulted in 1970 in⁶ $\text{Re}(\epsilon) = (1.7 \pm 0.3) \times 10^{-3}$ and $\text{Im}(\delta) = (-0.3 \pm 0.4) \times 10^{-3}$. $\text{Re}(\epsilon)$ describes T violation in K^0 - \bar{K}^0 mixing, here established with $\sim 5\sigma$, and δ describes CPT violation therein, compatible with zero. In the B^0 - \bar{B}^0 system, large CP violation was observed in 2001^{7,8} in $B^0 \rightarrow c\bar{c}K^0$ decays, but neither T nor CPT violation has been observed in B^0 - \bar{B}^0 mixing so far.

Weak-interaction mixing (Standard Model or beyond) in the two-state

system $\Psi = \psi_1 B^0 + \psi_2 \bar{B}^0$ is described by the evolution equation

$$i \frac{\partial}{\partial t} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} = \left[\begin{pmatrix} m_{11} & m_{12} \\ m_{12}^* & m_{22} \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix} \right] \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}, \quad (1)$$

with 7 real parameters m_{11} , m_{22} , Γ_{11} , Γ_{22} , $|m_{12}|$, $|\Gamma_{12}|$, and $\phi(\Gamma_{12}/m_{12})$. Two solutions of Eq. (1) have an exponential decay law. In lowest order of z and $1 - |q/p|$, as used throughout this presentation, they are given by

$$\begin{aligned} B_H^0(t) &= e^{-\Gamma_H t/2 - i m_H t} [p(1 + z/2) B^0 - q(1 - z/2) \bar{B}^0] / \sqrt{2}, \\ B_L^0(t) &= e^{-\Gamma_L t/2 - i m_L t} [p(1 - z/2) B^0 + q(1 + z/2) \bar{B}^0] / \sqrt{2}, \end{aligned} \quad (2)$$

with 7 real observables m_H , $\Delta m = m_H - m_L$, Γ_H , $\Delta\Gamma = \Gamma_H - \Gamma_L$, $|q/p|$, $\text{Re}(z)$, and $\text{Im}(z)$. The 7 observables follow from the 7 parameters, e.g.,

$$\left| \frac{q}{p} \right| = 1 - \frac{2 \text{Im}(\Gamma_{12}/m_{12})}{4 + |\Gamma_{12}/m_{12}|^2}, \quad z = \frac{(m_{11} - m_{22}) - i(\Gamma_{11} - \Gamma_{22})/2}{\Delta m - i\Delta\Gamma/2}. \quad (3)$$

In the K^0 system, the traditionally used observables are $\text{Re}(\epsilon) = (1 - |q/p|)/2$ and $\delta = -z/2$. T symmetry requires $|q/p| = 1$, and CPT symmetry $z = 0$. From Eqs. (2), we obtain the transition rates as function of the evolution time t . With $\Gamma = (\Gamma_H + \Gamma_L)/2$ and $|\Delta\Gamma| \ll \Gamma$, they are

$$\begin{aligned} R(B^0 \rightarrow B^0) &= e^{-\Gamma t} [1 + \cos(\Delta m t) - \text{Re}(z) \Delta\Gamma t + 2 \text{Im}(z) \sin(\Delta m t)]/2, \\ R(\bar{B}^0 \rightarrow \bar{B}^0) &= e^{-\Gamma t} [1 + \cos(\Delta m t) + \text{Re}(z) \Delta\Gamma t - 2 \text{Im}(z) \sin(\Delta m t)]/2, \\ R(B^0 \rightarrow \bar{B}^0) &= e^{-\Gamma t} [1 - \cos(\Delta m t)] |q/p|^2 / 2, \\ R(\bar{B}^0 \rightarrow B^0) &= e^{-\Gamma t} [1 - \cos(\Delta m t)] |p/q|^2 / 2; \end{aligned} \quad (4)$$

the first two depend only on z , the last two only on $|q/p|$. Since $\Delta\Gamma$ is unknown, the first rates determine only $\text{Im}(z)$, not $\text{Re}(z)$. Transitions into states decaying into CP eigenstates like $c\bar{c}K_S$, $c\bar{c}K_L$ are also sensitive to $\text{Re}(z)$ as shown below. The world average⁹ for $|q/p|$ is $1 + (0.8 \pm 0.8) \times 10^{-3}$. For $\text{Im}(z)$, *BABAR*¹⁰ determined with dileptons $(-14 \pm 7 \pm 3) \times 10^{-3}$. Using $c\bar{c}K$ decays, *BABAR*¹¹ found $\text{Re}(z) = (19 \pm 48 \pm 47) \times 10^{-3}$ in $88 \times 10^6 B\bar{B}$ events and Belle¹² $(19 \pm 37 \pm 33) \times 10^{-3}$ in $535 \times 10^6 B\bar{B}$ events. The present analysis from *BABAR*¹³ uses our final data set with $470 \times 10^6 B\bar{B}$ events.

Defining the decay amplitudes A for $B^0 \rightarrow c\bar{c}K^0$ and \bar{A} for $\bar{B}^0 \rightarrow c\bar{c}\bar{K}^0$, with $\lambda = q\bar{A}/(pA)$, and assuming (1) $\Delta\Gamma = 0$, (2) absence of decays $B^0 \rightarrow c\bar{c}\bar{K}^0$ and $\bar{B}^0 \rightarrow c\bar{c}K^0$, and (3) negligible CP violation in $K^0\bar{K}^0$ mixing, the decay rates of B^0 and \bar{B}^0 states into $c\bar{c}K_S$ and $c\bar{c}K_L$ are given by

$$R_i(t) = N_i e^{-\Gamma t} (1 + C_i \cos \Delta m t + S_i \sin \Delta m t), \quad (5)$$

with,¹³ in lowest order of the small quantities z , $|q/p| - 1$, and $|\lambda| - 1$,

$$\begin{aligned}
 C_1(B^0 \rightarrow c\bar{c}K_L) &= +(1 - |\lambda|) - \text{Re}(\lambda) \text{Re}(z) - \text{Im}(\lambda) \text{Im}(z), \\
 C_2(\bar{B}^0 \rightarrow c\bar{c}K_L) &= -(1 - |\lambda|) + \text{Re}(\lambda) \text{Re}(z) - \text{Im}(\lambda) \text{Im}(z), \\
 C_3(B^0 \rightarrow c\bar{c}K_S) &= +(1 - |\lambda|) + \text{Re}(\lambda) \text{Re}(z) + \text{Im}(\lambda) \text{Im}(z), \\
 C_4(\bar{B}^0 \rightarrow c\bar{c}K_S) &= -(1 - |\lambda|) - \text{Re}(\lambda) \text{Re}(z) + \text{Im}(\lambda) \text{Im}(z), \\
 S_1 &= +\text{Im}(\lambda)/|\lambda| - \text{Re}(z)\text{Re}(\lambda)\text{Im}(\lambda) + \text{Im}(z)[\text{Re}(\lambda)]^2, \\
 S_2 &= -\text{Im}(\lambda)/|\lambda| - \text{Re}(z)\text{Re}(\lambda)\text{Im}(\lambda) - \text{Im}(z)[\text{Re}(\lambda)]^2, \\
 S_3 &= -\text{Im}(\lambda)/|\lambda| - \text{Re}(z)\text{Re}(\lambda)\text{Im}(\lambda) + \text{Im}(z)[\text{Re}(\lambda)]^2, \\
 S_4 &= +\text{Im}(\lambda)/|\lambda| - \text{Re}(z)\text{Re}(\lambda)\text{Im}(\lambda) - \text{Im}(z)[\text{Re}(\lambda)]^2. \quad (6)
 \end{aligned}$$

Neutral B mesons in $BABAR$ are produced in the entangled two-particle state $(B^0\bar{B}^0 - \bar{B}^0B^0)/\sqrt{2}$ from $\Upsilon(4S)$ decays. With a flavor-specific first decay into $\ell^- X$ ($\ell^+ X$)^a at time t_1 , the remaining single-particle state is a B^0 (\bar{B}^0) at this time. Its rate for $c\bar{c}K$ decays at time $t_2 = t_1 + t$ is given by Eqs. (5) and (6). Decay pairs from the entangled two-particle state respect the two-decay-time formula,¹⁴ i.e., events with the $c\bar{c}K$ decay before the $\ell^\pm X$ decay have the same time dependence in $t_{c\bar{c}K} - t_{\ell X}$ as events with $\ell^\pm X$ as first decay. With the numeration in Table 1, events for $i = 5$ -8

Table 1. Decay pairs in Ref. 15 for the measurement of the decay-time dependences with the coefficients $C_1 \cdots C_8$ and $S_1 \cdots S_8$.

i	1	2	3	4	5	6	7	8
1st decay	$\ell^- X$	$\ell^+ X$	$\ell^- X$	$\ell^+ X$	$c\bar{c}K_L$	$c\bar{c}K_L$	$c\bar{c}K_S$	$c\bar{c}K_S$
2nd decay	$c\bar{c}K_L$	$c\bar{c}K_L$	$c\bar{c}K_S$	$c\bar{c}K_S$	$\ell^- X$	$\ell^+ X$	$\ell^- X$	$\ell^+ X$

follow Eq. (5) with $t = t_{\ell X} - t_{c\bar{c}K}$ and $C_i = C_{i-4}$, $S_i = -S_{i-4}$. The reconstruction of events and the determination of the coefficients $C_1 \cdots C_8$, $S_1 \cdots S_8$ are described in Ref. 15. The obtained values of the 16 coefficients with their uncertainties and correlations are used in Ref. 13 for a χ^2 fit of the parameters $\text{Im}(\lambda)$, $|\lambda|$, $\text{Im}(z)$, and $\text{Re}(z)$ to the expressions in Eq. (6), leading to the final results

$$\text{Im}(\lambda) = 0.689 \pm 0.034 \pm 0.019, \quad |\lambda| = 0.999 \pm 0.023 \pm 0.017, \quad (7)$$

$$\text{Im}(z) = 0.010 \pm 0.030 \pm 0.013, \quad \text{Re}(z) = -0.065 \pm 0.028 \pm 0.014, \quad (8)$$

^aIn addition to prompt charged leptons from inclusive semileptonic decays $\ell^\pm \nu X$, Ref. 15 used charged kaons, charged pions from D^* decays and high-momentum charged particles in the flavor-specific samples $\ell^\pm X$.

where the first (second) errors are statistical (systematic). The sign of $\text{Re}(z)$ requires the sign of $\text{Re}(\lambda)$. Since $\text{Im}(\lambda)$ and $|\lambda|$ do not fix this sign, additional information has to be used^b for taking $\text{Re}(\lambda)$ negative. The final results are independent¹³ of the assumption $\Delta\Gamma = 0$. Inserting the world average⁹ for $|q/p|$ into the definition of λ , we obtain

$$|\bar{A}/A| = 0.999 \pm 0.023 \pm 0.017. \quad (9)$$

Under the assumption that A and \bar{A} have a single weak phase, CPT symmetry requires¹⁶ $|\bar{A}/A| = 1$.

In conclusion: using $470 \times 10^6 B\bar{B}$ events, *BABAR* finds the results in Eqs. (8) and (9) in agreement with CPT symmetry in B^0 - \bar{B}^0 mixing and in $B \rightarrow c\bar{c}K$ decays. The result for $\text{Re}(z)$ sets a limit on SME coefficients.^{17,18} With $\Delta\Gamma \ll \Delta m$, and averaged over all sidereal times,

$$\beta^\mu \Delta a_\mu = \gamma \Delta a_0 - \beta_z \gamma \Delta a_z = \text{Re}(z) \times \Delta m, \quad (10)$$

where z is defined by the Earth's rotation axis. All B mesons in *BABAR* fly in a very narrow cone with¹⁸ $\gamma = 1.14$ and $\beta_z \gamma = 0.34$, resulting in

$$\Delta a_0 - 0.30 \Delta a_z = (-1.9 \pm 0.8 \pm 0.4) \times 10^{-14} \text{ GeV}. \quad (11)$$

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^bSee Ref. 13 and citations 19-22 therein.